The Influence of Metallicity on Star Formation in Protogalaxies

A.-K. Jappsen[*,†], S. C. O. Glover[†,**], R. S. Klessen[‡,†] and M.-M. Mac Low[**,‡]

[*]*Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada*
[†]*Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany*
[**]*Department of Astrophysics, American Museum of Natural History, New York, NY 10024-5192, USA*
[‡]*Zentrum für Astronomie der Universität Heidelberg, Institut für Theoretische Astrophysik, Albert-Ueberle-Str. 2, 69120 Heidelberg, Germany*

Abstract. In cold dark matter cosmological models, the first stars to form are believed to do so within small protogalaxies. We wish to understand how the evolution of these early protogalaxies changes once the gas forming them has been enriched with small quantities of heavy elements, which are produced and dispersed into the intergalactic medium by the first supernovae. Our initial conditions represent protogalaxies forming within a fossil H II region, a previously ionized region that has not yet had time to cool and recombine. We study the influence of low levels of metal enrichment on the cooling and collapse of ionized gas in small protogalactic halos using three-dimensional, smoothed particle hydrodynamics (SPH) simulations that incorporate the effects of the appropriate chemical and thermal processes. Our previous simulations demonstrated that for metallicities $Z < 10^{-3}\,Z_{\odot}$, metal line cooling alters the density and temperature evolution of the gas by less than 1% compared to the metal-free case at densities below $1\,\mathrm{cm}^{-3}$ and temperatures above 2000 K. Here, we present the results of high-resolution simulations using particle splitting to improve resolution in regions of interest. These simulations allow us to address the question of whether there is a critical metallicity above which fine structure cooling from metals allows efficient fragmentation to occur, producing an initial mass function (IMF) resembling the local Salpeter IMF, rather than only high-mass stars.

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INTRODUCTION

Population III stars are the first potential producers of UV photons that can contribute to the reionization process and are the first producers of the metals required for the formation of population II stars. Metals produced by the first stars will also be injected into some fraction of the ionized volume, and so will be present in gas falling into new or existing protogalactic halos. The question then arises as to how this low level of metal enrichment affects the ability of the gas to cool and collapse.

In [1], the collapse of cold, metal-enriched gas in a top-hat potential was simulated. These simulations included the effects of atomic fine structure cooling, but did not include cooling from H_2. In the absence of molecular cooling, fragmentation suggestive of a modern IMF was found to occur only for metallicities above a threshold value of $Z \simeq 10^{-3.5} Z_{\odot}$. However, the authors noted that the neglect of molecular cooling could be significant. In [2], Omukai et al. argued, based on the results of their detailed one-zone models, that molecular cooling would indeed dominate the cooling over many orders of magnitude in density. Also, by starting with cold gas, the authors of [1] implicitly assume that no extra entropy or energy has been added to the gas during its enrichment, although this is unlikely to be the case [3].

It is therefore important to consider whether a metallicity threshold appears in simulations with different initial conditions. In this paper, we examine a different, still idealized, set of initial conditions, using a more detailed treatment of the cooling and chemistry of the gas, and find no threshold. We argue that the transition from the primordial to the modern IMF therefore depends on the conditions under which stars form as much as on the metal abundances present.

NUMERICAL APPROACH

To help us to assess the influence of metals on the fragmentation properties of gas in small protogalactic halos, we have performed a number of numerical simulations. Here we present a portion of our results. Detailed discussion of the full set of simulations can be found in [4] (hereafter paper V). Our study requires us to follow the collapse of the gas over many orders of magnitude in density, and therefore the problem is well-suited for the use of a Lagrangian numerical method. We use SPH, a Lagrangian method described in [5], [6] and [7], in which the fluid is followed with an ensemble of particles.

Fluid properties at each point are computed by averaging over neighboring particles. The calculations presented in this paper use version 1 of the parallel SPH code GADGET [8]. In order to achieve a higher mass resolution, we refine the mass of the gas particles using a method known as particle splitting [9]. In [10], hereafter paper II, we presented low-resolution simulations that show that the density increases most rapidly close to the center of the dark matter halo. On-the-fly splitting with two levels of refinement at two different radii provides us with the highest mass resolution at the region of interest. In the region of collapse we can resolve Jeans masses down to 1.5 $M_{\odot}$, as compared to $M_{\rm res} = 200\ M_{\odot}$ in the low resolution simulations. We discuss the details of the implementation of the particle splitting algorithm in paper V.

As we want to represent gas that has collapsed beyond the resolution limit of the simulation in a numerically robust manner, we have modified the code to allow it to create sink particles – massive, non-gaseous particles, designed to represent dense cores, that can accrete gas from their surroundings but otherwise interact only via gravity [11]. Sink particles are created once the density rises above $10^4\,{\rm cm}^{-3}$ and are endowed with an accretion radius of 0.3 pc. On every time step, any gas within this accretion radius that is gravitationally bound to the sink particle is accreted by it. The design and implementation of our sink particle algorithm is discussed in more detail in [12].

CHEMISTRY AND COOLING

We have further modified GADGET to allow us to follow the non-equilibrium chemistry of the major coolants in both primordial and low-metallicity gas. Our chemical model is presented in [13] and [14] (hereafter papers I and III). Provided that carbon and oxygen are amongst the most abundant metals, the major coolants will be largely the same as in local atomic and molecular gas, namely H_2, HD, C, C^+, O, Si, Si^+, CO, OH and H_2O [2]. We therefore follow the abundances of these ten species, together with an additional 29 species that play important roles in determining the abundances of one or more of these coolants. Our chemical network contains a total of 189 collisional gas-phase reactions between these 39 species, as well as 7 grain surface reactions, 43 reactions involving the photoionization or photodissociation of chemical species by ultraviolet radiation, and 8 reactions involving cosmic rays. For simplicity, in the simulations presented in this paper we do not include the effects of dust, UV radiation or cosmic rays, and so use a simplified version of the model that contains only the collisional reactions. The thermal evolution of the gas in our simulations is modelled using a cooling function that includes the effects of atomic fine structure cooling from C, C^+, O, Si and Si^+, rotational and vibrational cooling from H_2, HD, CO and H_2O, Lyman-α cooling, Compton cooling, and H^+ recombination cooling, as well as a number of other processes of lesser importance. For additional details of our chemical networks and cooling function, please consult papers I and III; further details of their implementation within Gadget are also given in paper II.

INITIAL CONDITIONS

Our initial conditions are based on those used in paper II, although collapse is followed to much higher density in the current work. We study protogalaxies forming from fully ionized gas with initial temperature $T_g = 10^4$ K, representing a fossil H II region [3] polluted by supernovae from the ionizing object. We model one such halo by using a fixed background potential with a spherically symmetric density profile [15]. We study the evolution both of zero-metallicity, primordial gas and of metal-enriched gas with a metallicity $Z = 10^{-3} Z_{\odot}$. To simplify the discussion of our simulation results, we take as a fiducial example a halo with a dark matter mass $M_{\rm dm} = 7.8 \times 10^5\,M_{\odot}$, an initial redshift $z_i = 25$, and a spin parameter $\lambda = 0.05$. For this example halo, the virial temperature $T_{\rm vir} = 1900\,{\rm K}$, the virial radius $r_{\rm vir} = 0.1\,{\rm kpc}$, and the truncation radius $r_t = 0.49\,{\rm kpc}$, where both radii are given in physical units. The scale radius r_s of this example halo is 29 pc, and the full computational volume is a box of side length 1 kpc. The gas mass is $M_g = 0.19\,M_{\rm dm}$.

RESULTS AND DISCUSSION

In the simulations presented here we focus on gas with a metallicity $Z = 10^{-3}\,Z_{\odot}$. This metallicity is at the upper limit of the range of values proposed for the so-called critical metallicity $Z_{\rm crit}$, the value of the metallicity at which efficient fragmentation and low-mass star formation is hypothesized to first occur [1, 2, 16, 17]. It is also comparable to the globally averaged metallicity produced by the sources responsible for reionization [see e.g. 18].

In Figure 1 we compare the temperature-density evolution of the run with primordial gas and the run with enriched gas. The two runs differ by less than 10% up to densities of $n = 10^4\,{\rm cm}^{-3}$. This result demonstrates that the cooling of the gas is barely influenced by the presence of metals: fine-structure cooling contributes only marginally to the total cooling rate. H_2 is the dominant coolant, rather than metal fine structure lines. At first sight, the fact that fine structure cooling from metals has

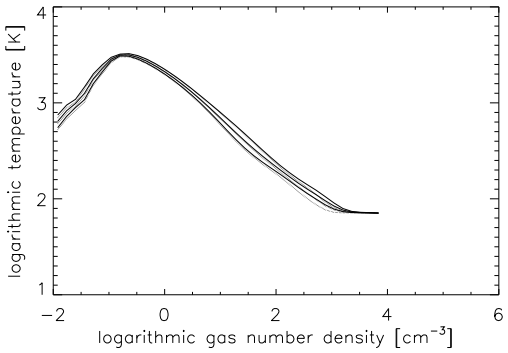

FIGURE 1. Gas temperature vs. number density for the runs with metallicities 0.0 (*solid line*), 10^{-3} (*dotted line*), and $10^{-1}\,Z_{\odot}$ (*dashed line*). The spin parameter of the runs is 0.05. The time of the plot is half a Hubble time. The thin lines show the 1-σ deviation.

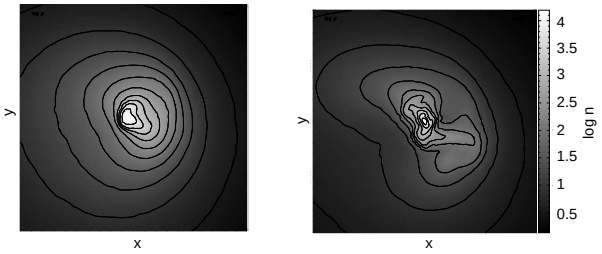

FIGURE 2. Cut at $z = 0.5\,\mathrm{kpc}$ through the gas number density for the run with zero metallicity (*left panel*) and the run with a metallicity of $Z = 10^{-3}Z_{\odot}$ (*right panel*). We show a box with a size of 20 pc.

little impact on the thermal or dynamical evolution of the gas at metallicities below $0.1\,Z_{\odot}$ is somewhat surprising, given that it was previously found that gas with a metallicity of only $Z = 10^{-3}\,Z_{\odot}$ could cool rapidly and fragment even in the complete absence of molecular hydrogen [1]. However, this difference in conclusions appears to be a consequence of the different initial conditions used in the two sets of simulations, and the difference in the physics included. The simulations presented in [1] neglected molecular cooling, and started with cold ($T_{\mathrm{initial}} = 200\,\mathrm{K}$), low ionization ($x_e = 10^{-4}$) gas in a flat, top-hat dark matter potential lacking a central condensation, although with local density perturbations. In these simulations, the gas cools, collapses and fragments only if the metallicity is high enough to render the cooling time shorter the the local dynamical timescale. With our arguably more realistic initial conditions, and, crucially, with our inclusion of H_2, we find no metallicity threshold – H_2 cooling alone is sufficient to allow the gas to collapse, but the collapsing gas does not fragment (see Figure 2 and [19]). In [4], we present a set of additional runs with metallicities up to $Z = 10^{-1}Z_{\odot}$ that confirm this result. We conclude that the transition from the primordial to the modern-day IMF therefore depends on the conditions under which stars form as much as on the metal abundances present. The actual conditions that are appropriate for second generation star formation still need to be determined in detail by observation and modeling of galaxy formation.

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REFERENCES

1. Bromm, V., Ferrara, A., Coppi, P. S., & Larson, R. B. 2001, *MNRAS*, **328**, 969
2. Omukai, K., Tsuribe, T., Schneider, R., & Ferrara, A. 2005, *ApJ*, **626**, 627
3. Oh, S. P. & Haiman, Z. 2003, *MNRAS*, **346**, 456
4. Jappsen, A.-K., Mac Low, M.-M., Glover, S. C. O., Klessen, R. S. 2007, in preparation (paper V)
5. Benz, W. 1990, in Numerical Modelling of Nonlinear Stellar Pulsations Problems and Prospects, ed. J. R. Buchler (Dordrecht: Kluwer), 269
6. Monaghan, J. J. 1992, *ARA&A*, **30**, 543
7. Monaghan, J. J. 2005, *Rep. Prog. Phys.*, **68**, 1703
8. Springel, V., Yoshida, N., & White, S. D. M. 2001, *New Astron.*, **6**, 79
9. Kitsionas, S. & Whitworth, A. P. 2002, *MNRAS*, **330**, 129
10. Jappsen, A.-K., Glover, S. C. O., Klessen, R. S., & Mac Low, M.-M. 2007, *ApJ*, **660**, 1332 (paper II)
11. Bate, M. R., Bonnell, I. A., & Price, N. M. 1995, *MNRAS*, **277**, 362
12. Jappsen, A.-K., Klessen, R. S., Larson, R. B., Li, Y., & Mac Low, M.-M. 2005, *A&A*, **435**, 611
13. Glover, S. C. O., Jappsen, A.-K., 2007, *ApJ*, **666**, 1 (paper I)
14. Glover, S. C. O. 2007, in preparation (paper III)
15. Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, *ApJ*, **490**, 493
16. Bromm, V. & Loeb, A. 2003, *Nature*, **425**, 812
17. Schneider, R., Ferrara, A., Natarajan, P. & Omukai, K. 2002, *ApJ*, **571**, 30
18. Ricotti, M. & Ostriker, J. P. 2004, *MNRAS*, **350**, 539
19. Jappsen, A.-K., Klessen, R. S., Glover, S. C. O., & Mac Low, M.-M. 2007, in preparation (paper IV)